5.2 MEASUREMENTS OF WATER VAPOR AND CO_2 FLUXES PRODUCED BY A PRESCRIBED PRAIRIE FIRE USING A MICROMETEOROLOGICAL FLUX TOWER AND TETHERED BALLOON SOUNDING SYSTEM

C. B. Clements*[1], B. E. Potter[2], S. Zhong[1], G. Aumann[1], M. D. Jiang[1], S. Street[1], and M. R. Patel[1]

[1] University of Houston, Houston, TX
[2] USDA Forest Service, East Lansing, MI

1. INTRODUCTION

Wildland and prescribed fires are known to change atmospheric environments by producing heat and chemical species such as carbon dioxide and aerosols. Less recognized is the fact that fires can also modify the dynamic conditions of the lower atmosphere by releasing large amount of moisture. Few studies have discussed the release of moisture by fires and mostly with only an indirect acknowledgement (Stocks and Flannigan 1989; Goens and Andrews 1998; Potter 2005). So far, there have been no direct measurements of the amount of water vapor released during an actual forest or range fire due largely to the dangers of the fire environment. In many cases, either the researcher or the equipment would be in danger of injury, damage, or destruction. In others, the duration and location of a fire may preclude instrument deployment. While aircraft may fly through fire plumes, their altitude and speed may dilute any moisture signal to such an extent that measurements are inconclusive.

In this paper, we present what is to our knowledge the first in-situ measurement of water vapor fluxes, in addition to heat and CO_2 fluxes, within a prescribed prairie fire along the Texas Gulf Coast. The measurements are used to evaluate estimates from bulk theoretical calculations on the amount of added water vapor to the atmosphere from a fire.

2. SITE, INSTRUMENTATION, AND SYNOPTIC CONDITIONS

The observations of the prescribed burn took place at the Houston Coastal Center (HCC) located in central Galveston County near La Marque, Texas approximately 45 km southeast of the Houston Metropolitan Area and 22 km from the western shores of Galveston Bay. HCC has a number of small to medium sized prairies that are categorized as Texas Gulf Coast Tall-Grass Prairies consisting of a mixture of native grasses including Big Bluestem (*Andropogon gerardi*), Little Bluestem (*Schizachyrium scoparium*), and Long Spike Tridens (*Tridens strictus*). The prairie that was burned is 155 acres (0.63 km^2) in size and is considered one of the largest, undisturbed coastal prairies on the Gulf Coast of the United States. At the time of the prescribed fire, spring vegetation was just beginning to emerge and the cured, dead grasses from the previous year remained exposed and available for the fire to consume.

The synoptic conditions on the day of the prescribed burn (Feb. 17, 2005) were typical of a post-frontal environment with no precipitation. A shallow layer of relatively colder and drier air moved through the region the previous night in the form of a shallow cold front. Winds near the surface were 5-7 m s^{-1} from the north-northeast which prevailed throughout the period of the prescribed burn. Above this shallow layer (> 500 m AGL) winds were westerly. For smoke management purposes this synoptic condition was nearly ideal because immediately north of HCC there is a business district while areas south of the site all the way to the Gulf Coast are more rural and sparsely developed. That morning during the burn, the boundary layer depth was low, allowing the moderate north-northeasterly winds within the boundary layer to carry the smoke plume to the south-southwest towards the undeveloped areas.

During the prescribed burn, measurements of turbulent heat, water vapor and CO_2 fluxes were obtained by instruments mounted on a 42 m guyed tower located in the northern half of the prairie (Fig. 1). High-frequency momentum and temperature were measured using a R. M. Young 81000 3-D sonic anemometer at a height of 9.8 m AGL while a Li-Cor 7500 open path infrared gas analyzer collected high frequency data of CO_2 and H_2O concentrations. A Campbell Scientific, Inc. (CSI) CR-5000 data logger sampled both instruments at a frequency of 10 Hz, and turbulent fluxes were computed using eddy-covariance

---

* - *Corresponding author's address*: Craig Clements, 312 S and R 1, 4800 Calhoun Rd., Houston, TX 77204-5007, cbclements@uh.edu

techniques. In addition to turbulent fluxes, 5-minute mean meteorological variables were also measured by the tower at three levels (3, 21.7, and 32.2 m) using CSI, Inc., CS-500 temperature/humidity probes and R.M. Young 5103 propeller anemometers. The mean variables were recorded by a CSI CR-23X data logger every 1 s and averaged for 5 min. The week leading to the day of the prescribed fire had sufficient rainfall so that the soil was nearly saturated. There was standing water at the base of the instrument tower, extending several meters outward and providing a small protective area for the tower where fire would not penetrate and risk damaging the instruments.

Figure 1. Map of experiment site and instrument locations. Tower location is indicated by the large x and the location of the tethersonde system is indicated by the circle.

A tethered balloon sounding system was also placed downwind of the fire at the far southwest corner of the prairie (Fig. 1) to provide vertical profiles of temperature, relative humidity, wind speed, and wind direction at a frequency of 1 s. While the original plan was to make continuous soundings throughout the entire burn period, strong winds with gusts of ~ 12 m s^{-1} and heavy smoke from the fire forced the balloon operators to terminate the measurements after the first sounding taken around 1030 CST, right after the start of the back burn.

An initial back burn was started at 0900 CST in the southwest corner and continued for about 150 m. Fire crew members with drip torches then (approximately 0940 CST) lit additional back fires to create protected perimeters around the radio shed just west of the instrument tower and around the guy wires supporting the instrument tower. When these fires had progressed to the point where the fire burn boss was assured the structures were safe, the crew resumed ignition along the southern edge of the field, proceeding counterclockwise until they reached the edge of the wooded area, approximately in the middle of the prairie's northern boundary. At this point, the fire ran with the wind until it reached the water-filled ditch on the west side of the field or the back burn area on the southern edge. Active burning was complete by approximately 1045 CST, with smoldering continuing for several hours in parts of the field.

3. RESULTS OF THE OBSERVATIONS

3.1 Tethersonde Measurements

The potential temperature and water vapor mixing ratio profiles measured by the single tethersonde sounding during the preliminary back burning of the southern perimeter of the prairie are shown in Fig. 2. The atmosphere in the boundary layer was near neutral as revealed by the potential temperature profile that was nearly constant with height. The lower atmosphere was also quite dry for the coastal environment in Galveston, with a boundary layer water vapor mixing ratio around 6 g kg^{-1}, as compared to the more typical value of over 10 g kg^{-1} for this time of the year.

Although the area of the back burn (a small control burn before the initial prairie is burned) was only about 75 m^2, the plume generated by the fire is clearly visible in the tethersonde sounding profile obtained approximately 50 m downwind from the back burn. As indicated by a sudden increase in potential temperature and water vapor mixing ratio in the vertical profile, the fire plume had an approximate thickness of 10 m centered around 20 m AGL. The sharp decrease of both temperature and mixing ratio within the plume suggested that the plume was actually comprised of two layers each of ~ 5 m in thickness. Potential temperature increased from 285.8 K to 291.4 K in the lower layer and from 286.1 K to 288.8 K in the upper layer. While this plume does not represent the main plume from the full prairie burn, it does indicate a dramatic increase in not only the potential temperature, as would be expected, but in water vapor as well. The mixing ratio of water vapor in Fig. 2 increased from 6.08 g kg^{-1} to 8.01

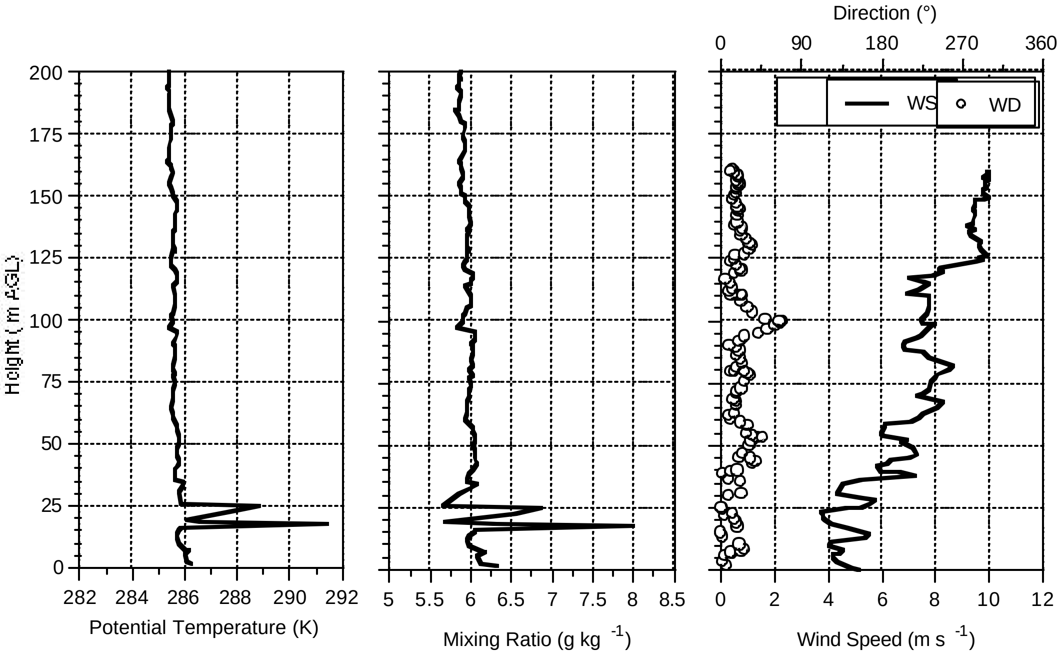

Figure 2. Vertical profiles of potential temperature, mixing ratio, wind direction and wind speed from Tethersonde measurement at 0910 CST.

g kg^{-1} in the lower layer and from 5.67 g kg^{-1} to 6.86 g kg^{-1} in the upper layer (changes of 1.93 g kg^{-1} and 1.19 g kg^{-1}, respectively). The net moisture increase of 1-2 g kg^{-1} (20-30% of the background moisture) is notable considering the small area of the back burn.

3.2 Tower measurements

While 5 minute mean quantities do not show the changing atmospheric conditions during the burn in great detail, there are some interesting features that warrant mention. The time series of temperature from the three levels on the tower are shown in Fig. 3. In the morning hours before the burn, the mean temperature decreased from the lower to higher levels at a rate close to the adiabatic lapse rate (~ 1 ^{o}C per 100 m increase in height), indicating a neutral surface layer, which is consistent with the tethersonde profile downwind from the tower.

A sudden temperature jump of about 3^{o} C occurred at 3 m level around 0945 CST, while a more substantial increase of 4-7^{o} C occurred later at the two upper levels. Video filmed from a nearby tower during the burn suggested that the early increase at the 3 m level was due to the initial back burn at the tower's periphery, while the more significant increase in temperature at upper levels corresponds to the main fire plume impinging upon the tower minutes after the northern edge of the prairie was ignited. This same pattern is seen in the mixing ratio values for each level. The initial, near-surface plume from the back burn produced a small spike in mixing ratio at 3 m around the same time when temperature at the 3 m level increased suddenly. More significant increases in water vapor mixing ratio of 0.5 – 1 g kg^{-1} occurred at the higher levels later as the main plume passed the tower. The stronger increases in both mean temperature and mixing ratio observed later were due to the larger burn area and higher burn intensity, which produced a taller and stronger plume. Wind speed increased with height before and after the burn, as would be expected. But when the tower intercepted the main plume, the wind speed at the three levels converged, suggesting enhanced turbulent mixing by the fire.

Significant increases in the turbulent fluxes due to the fire plume are clearly illustrated in the time series plot in Fig. 4. Values of CO_2 flux increased from -0.08 mg m^{-2} s^{-1} to 171.0 mg m^{-2} s^{-1}. Sensible heat flux increased from 38.4 W m^{-2} to 1183.5 W m^{-2} and latent heat flux increased from 29.7 W m^{-2} to 376.6 W m^{-2}. An examination of time series plots of the high frequency data (not shown) between 0930 and 1100 CST revealed a clear distinction of small plumes passing the tower during the back burn (i.e.,0945, 0948 CST) and the main plume passing at approximately 1019 CST with temperatures increasing from 14°C to a maximum of approximately 34°C. Increases in both H_2O and CO_2 concentrations correlate well with the temperature increases, indicating these

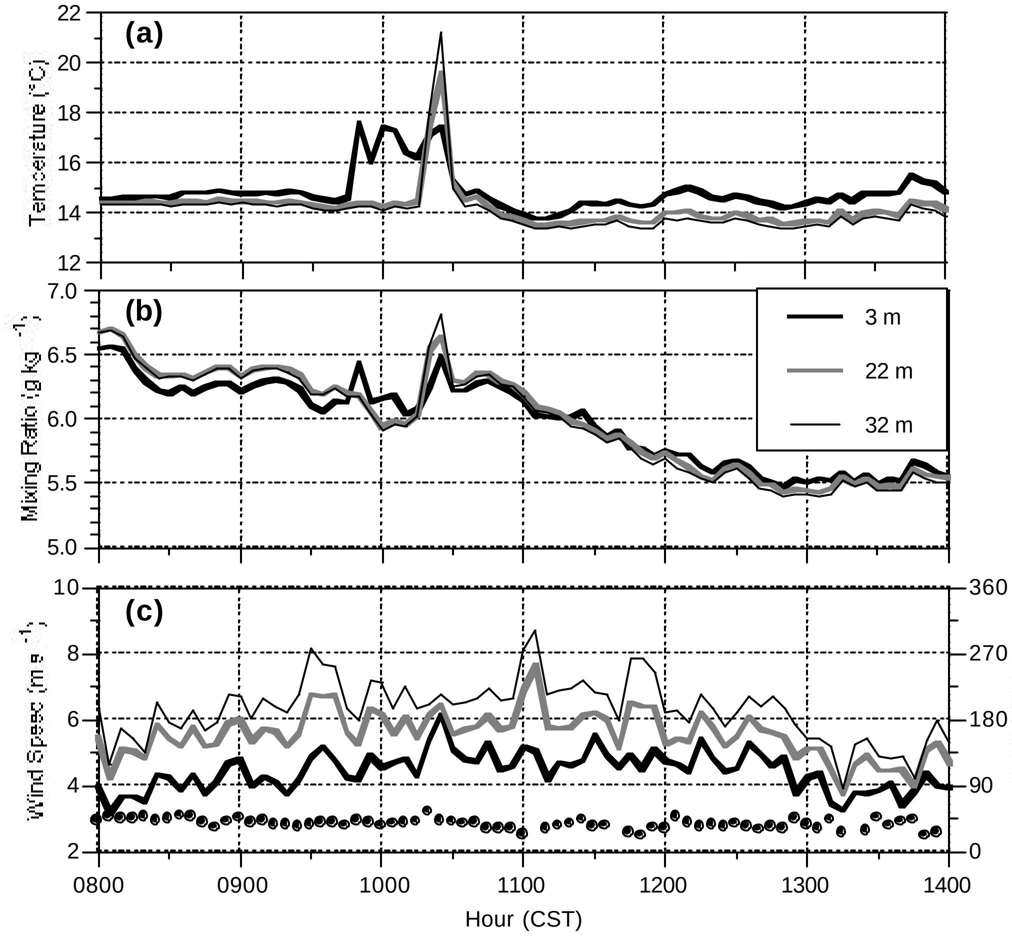

Figure 3. Time series of 5 min mean (a) temperature, (b) water vapor mixing ratio, (c) wind speed at each height (3 m, 21.2 m, 32.2 m) on the tower. Wind direction is indicated by the dots in panel (c).

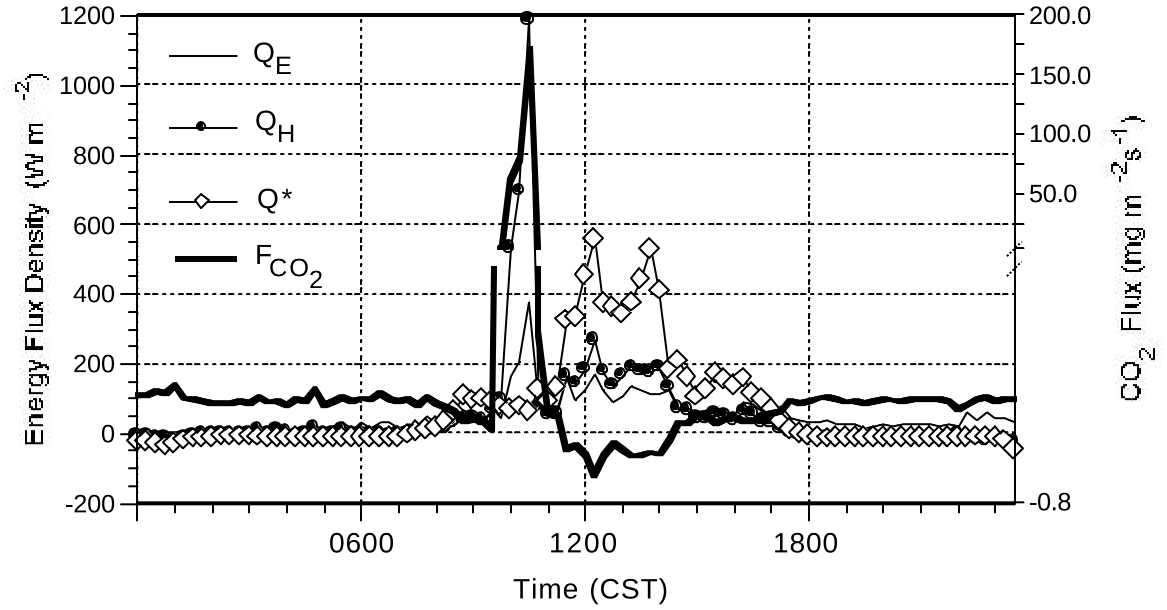

Figure 4. Time series of 15-min mean turbulent fluxes of energy (Q*, net radiation; Q_H, sensible heat; and Q_E, latent heat) and CO_2 (F_{CO2}) during the fire on 17 Feb. 2005.

observed spikes are smoke plumes. During the entire burn period, including the back burning around the tower base, CO_2 concentration increased from approximately 378 ppm to over 2560 ppm while water vapor mixing ratio increased from approximately 6.9 g kg $^{-1}$ to 9.08 g kg $^{-1}$, an increase of 2.18 g kg $^{-1}$.

4. THEORETICAL COMPARISONS

A simple bulk aerodynamic model provides a first order estimate of the amount of water vapor one would expect as a combustion byproduct from a fire such as this. This model simply determines the mass flux of water into the air, and based on wind speed and estimated vertical mixing depth, relates that water flux to the volume of air it enters. Assuming uniform mixing in the vertical and a linear fire that is much longer perpendicular to the direction of fire spread than the depth of the air layer involved, the change in mixing ratio due to complete combustion is

$$\Delta q_v = 100\frac{f u_f (0.56+M)}{H_M (u-u_f)} \tag{1}$$

where Δq_v is the change in mixing ratio (stated as mass of water per mass of air, in g kg^{-1} here); u is the horizontal environmental wind speed (m s^{-1}); u_f is the rate of fire's spread (m s^{-1}); M is the fractional moisture content of the fuel (kg of water per kg of oven-dry fuel weight); f is the fuel load (kg m^{-2}); and H_M is the vertical plume depth (m). The constant value of 0.56 represents the ratio of the mass of water produced by combustion of dry plant tissue to the mass of the plant tissue. For this equation, we have assumed that the density of air is approximately 1 kg m^{-3}.

Based on standard fuel models used in fire behavior analyses (Anderson 1982), the short grass at the study site is represented by a fuel load, f, of approximately 0.16 kg m^{-2}. Using the fire behavior analysis program *BehavePlus* version 2.0 (Andrews et al. 2005) and the prevailing conditions at the site, we have estimated that the mean winds were approximately 5 m s^{-1}; dead fuel moisture (M) was approximately 0.08; and maximum fire spread rate (u_f) was 1.1 m s^{-1}.

The tethersonde data show water vapor mixing ratio increases coincident with temperature increases. The data also suggest that, ignoring the apparent undisturbed layer at 20 m, the plume was about 10 m in vertical extent as it passed the tethersonde instruments. Using 10 m as an estimate of H_M and the other values presented in the previous paragraph, the estimated water vapor mixing ratio increase from the fire based on Eq. (1) is 2.9 g kg^{-1}.

An idealized plume from a surface fire will rise at an angle dependent on ascent rate and mean horizontal winds, with greater ascent or weaker horizontal winds yielding a more vertical plume. Turbulent mixing of the plume would be greater on the downwind side. The least diluted air would always be on the upwind side of the plume, with dilution and mixing increasing with height and distance from the upwind plume edge. Because the plume leans in the same direction it moves, it would pass over a given location (such as the instrument tower) at upper levels and gradually descend. As it approaches the location, smoke density, CO_2, H_2O, and temperature perturbations at a given height will increase. If the progress of the fire towards the location were to stop for some reason, instruments below some height may never detect the plume and lower levels might detect only diluted air, never encountering the less diluted air on the upwind side of the plume. In the current study, the back burn around the guy wires stopped the fire's progress towards the instrument tower, prohibiting the 3 m sensors from ever detecting the plume of the main fire.

The 5-minute averaged observations are consistent with the idealized plume described above. The data only allow determination of when the plume first reached a given level to within 5 minutes, and as such we cannot determine whether the plume did actually reach the 32 m sensors prior to reaching the 22 m sensors. The temperature and moisture measurements at 32 m and 22 m do show higher values at the higher altitude, though. Furthermore, once air from the combustion zone has been heated and moistened, assuming conservation of water substance and thermal energy, subsequent mixing will deplete the initial perturbation of moisture and temperature proportionally. Computing average temperature and mixing ratio values over the time range 0900 to 1200 CST and using perturbation values taken at 1025 CST, the ratio of peak perturbation moisture at 22 m to 32 m is 0.73 and the analogous ratio for perturbation temperature is also 0.73.

One can also perform the same bulk aerodynamic estimate and comparison with the tower data. Using the photos and video recording of the tower during the fire, we can estimate that the plume thickness, H_M, at 1025 CST was between 10 and 15 m. The average wind speed for the 22 and 32 m levels at 1025 CST was 6.6 m s^{-1}. These values, with the same rate of spread and fuel load values as earlier, yield an estimated mixing ratio perturbation of 2.0 g kg^{-1} (for a 10 m thick plume).

The above estimates based on the simple aerodynamic model are limited by the accuracy of the parameters in Eq. (1). For example, the rate of spread, u_f, is an estimated maximum. If the real rate was lower – which may be a fair assumption, given the wet-field conditions – then the perturbation moistures would be lower, and the calculations would agree better with observations. Furthermore, air density on this day was probably closer to 1.2 kg m^{-3} since p=1020 mb and T=15°C which may also cause a lower q_v estimate. Finally, the fuel load is an estimate that would also have an impact on the estimated q_v value.

5. CONCLUSIONS

We have presented in-situ measurements of heat, water vapor and CO_2 fluxes during a prescribed prairie fire along Texas Gulf Coast using instruments mounted on a 42-m micrometeorological flux tower within the prairie fire and a tethered balloon sounding system downwind of the fire. The observations show, as expected, a sharp increase in mean temperature as well as heat fluxes and CO_2 fluxes associated with the passage of fire plumes. Both measurement platforms also revealed a strong increase in water vapor of approximately 2 g kg^{-1} within the fire plume, which is in good agreement with the estimate of water vapor increase obtained using a simple bulk aerodynamic model. Although the data set was limited to one fire, the results confirmed quantitatively for the first time Potter's (2005) theoretical argument that a wildland or grass fire may add 1 to 5 g kg^{-1} of water vapor to plume air.

6. ACKNOWLEDGEMENTS

We thank the Burn boss, Mr. Mark Krammer, from the Armand Bayou Nature Center for his coordination and management of the burn. This research was support by EPA Grant R-83037701 and by an internal grant from Houston Coastal Center.

7. REFERENCES

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 22 p.

Andrews, P.L., C.D. Bevins, R.C. Seli, 2005. BehavePlus fire modeling system, version 3.0: User's Guide. Gen. Tech. Rep. RMRS-GTR-106WWW. Ogden, UT: Department of Agriculture, Forest Service, Rocky Mountain Research Station. 142 p.

Goens, D.W. and P.L. Andrews, 1998. Weather and fire behavior factors related to the 1990 Dude fire near Payson AZ. In *Proceedings of the 2nd Conference on Fire and Forest Meteorology*, American Meteorological Society, Phoenix, AZ, 11-16 January 1998. pg. 153-158.

Potter, B.E., 2005. The role of released moisture in the atmospheric dynamics associated with wildland fires. *International Journal of Wildland Fire*. **14**(2):77-84.

Stock, B.J. and M.D. Flannigan, 1989. Analysis of the behavior and associated weather for a 1986 northwestern Ontario wildfire: Red Lake #7. In *Proceedings of the 10th Conference on Fire and Forest Meteorology*, Forestry Canada, Ottawa, Canada, 17-21 April 1989. pgs. 94-100.